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HUMAN ERROR MODELING PREDICTIONS: INCREASING OCCUPATIONAL SAFETY USING HUMAN PERFORMANCE MODELING TOOLS

Brian F. Gore and Kevin M. Corker

San Jose State University/NASA Ames Research Center, Moffett Field, CA - 94035-1000

Abstract: The use of computer-aided job analysis tools has been increasing in the recent past as a result of decreases in computational costs, augmentations in the reality of the computer-aided job analysis tools, and usefulness of the output generated from these tools. One tool set known as integrated Human Performance Modeling (HPM) is a human-out-of-the-loop (HOOTL) computational methodology used to generate predictions of complex human-automation integration and system flow patterns. These tools provide computational representations of humans incorporating physical, cognitive, perceptual, and environmental characteristics. Increasingly complex automation leads to a new class of errors and error vulnerabilities. Hollnagel's (1993) Contextual Control Model (CoCoM) will be used as the human error theory behind a HOOTL simulation using Air Man-machine Integration Design and Analysis System (Air MIDAS) to evaluate complex human-automation integration considerations currently underway at NASA Ames Research Center. This paper will highlight the importance of the physical and cognitive link of a specific task and will outline attempts being made to understand the factors underlying human error, a critical consideration of human-complex system performance.

1. JOB ANALYSIS: PHYSICAL VERSUS COGNITIVE MODELS

Current job analysis activities focus on the development of procedures that integrate ergonomic stresses across body parts of major interest (e.g., lower back, upper extremities, and neck) and allow in-plant teams to rank the seriousness of exposures across different jobs (Medsker & Campion, 1997). The themes that are examined in these exposures range from job design issues (self management, participation, task variety, significance and identity), to job interdependence of tasks, to job composition (flexibility), to job context (training, support, cooperation among members) and to job process issues (workload, social support, member cooperation). This method of analyzing the job is often subjective in nature and over-relies on the physical performance of a task making the process limited in cross-domain application. In these ergonomic programs, there is little significance given to the physical-cognitive job interactions that may occur. This method of analyzing a job assumes that human behavior is sequential when viewed in hindsight but this orderliness is really just an artifact of the asymmetry of time (Hollnagel, 2000).

2. HUMAN-OUT-OF-THE-LOOP (HOOTL) SIMULATIONS

Many different forms of Human-Out-Of-The-Loop (HOOTL) simulations exist - these can range from anthropometric simulations of human performance to procedural static models, through to more complex dynamic representations of human performance within an operating environment. These latter techniques include integrated human performance models which use computer models of human performance where human characteristics, based on empirical research, are embedded within a computer software structure to represent the human operator (Laughery & Corker, 1997; Gore 2000). This virtual operator is then set to interact with computer-generated representations of the operating environment. HOOTL simulations can therefore be used at an earlier process in the development of a product, system or technology than waiting for the concept to be fully designed and used in practice (human in the loop tests). The system model development process allows the designer of the product, system or technology to fully examine many aspects of human-system performance with the new technologies. The model of human performance enables predictions of emergent behavior based on elementary perception, attention, working memory (WM), long-term memory (LTM) and decision-making models of human behaviors. This modeling approach focuses on micro models of human performance that feed-forward and feedback to other constituent models in the human system depending on the contextual environment that surrounds the virtual operator. These complex HOOTL simulation tools permit researchers to formulate procedures, generate hypotheses, and identify variables for Human in the Loop simulations (Gore & Corker, 2000b). One criticism of HOOTL tools has been that the software only predicts input-output behavior in mechanistic terms (Craik, 1947). The integrated and emergent structure of the tools however does more than solely represent input-output behavior, it attempts to prescribe how sequences of actions are planned and not simply prescribe a sequence of actions. The framework integrates many aspects of human performance

allowing each micro model component to behave in its required method, the integration of which replicates a human (Gore & Corker, 2000b). Hollnagel (2000) indicates this as being critical for developing a good model. The output measures of interest for HOOTL simulation efforts have traditionally included task demands, (mental) workload, task load, information load, attention demands, stress and procedural timing measures. These measures have been validated on a number of occasions across many different domains ranging from helicopter operations (Atencio, 1998), nuclear power-plant control electronic list design for emergency operations (Corker, 1994), to advanced aviation concepts (Corker et al., 2000).

3. SYSTEM PERFORMANCE AND THE EMERGENT HOOTL SIMULATIONS

The recent growth in HOOTL simulation tools has focused on the study of human performance interacting with systems (Gore & Corker, 2000a) and to support prediction of future system state (Lee, 1998). These hybrids of continuous control, discrete control and critical decision-making models have been undertaken to represent the "internal models and cognitive function" of the human operator in complex control systems, and involve a critical coupling among humans and machines in a shifting and context-sensitive function. A pictorial representation of one integrated, emergent HOOTL simulation tool co-developed by NASA Ames Research Center (ARC) and San Jose State University (SJSU) primarily for aviation-related applications termed Air Man-machine Integration Design and Analysis System (Air MIDAS) can be found in Figure 1a. The visualization component of the Core MIDAS software developed by the Army and NASA ARC in Figure 1b exemplifies the cognitive and physical visualization of the linkage. This graphic demonstrates an anthropometric figure interacting with an environment (top left), a view from the figure's eyes (top right), six-channel workload (low left) and situation awareness (low right). The purpose of including the Core MIDAS portion of this graphic is to demonstrate the visualization of the physical and the cognitive worlds in a computer-aided fashion. We will focus on the underlying Air MIDAS cognitive structures.
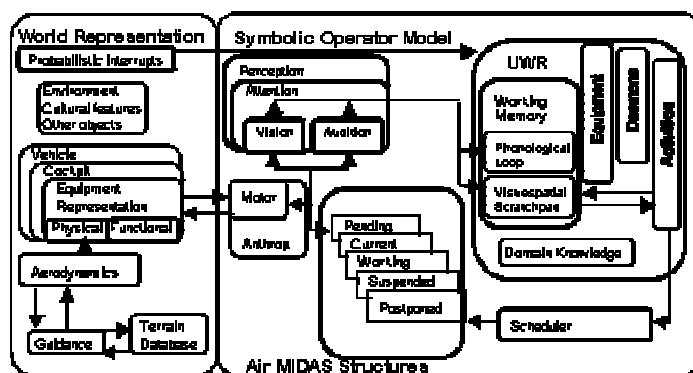

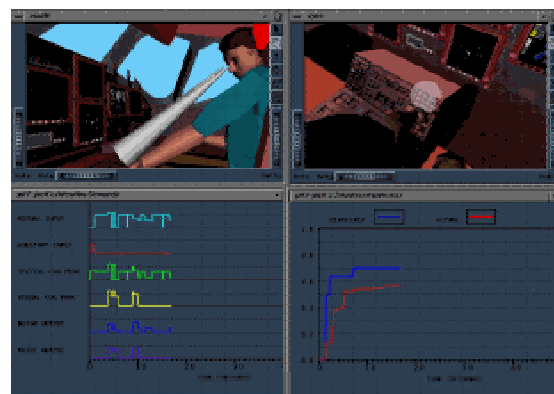Fig 1a. Air MIDAS underlying operational structures   Fig 1b. Core MIDAS visualization

Air MIDAS is an "emergent" model of human performance – one that is based on the mechanisms that underlie and cause human behavior (Laughery & Corker, 1997). The main components of the emergent model shown in Figure 1a comprise the simulated representation of the real world within which the virtual operator modeled by Air MIDAS exists, and a symbolic operator model (SOM) that represents perceptual and cognitive activities of an agent. An important element of the SOM is the Updateable World Representation (UWR). The world representation information (environment, crew-station, vehicle, physical constraints and the terrain database) is passed through the perceptual and attention processes of the SOM to the UWR. The UWR represents the agent's WM, domain knowledge and task activity structure to be completed. This UWR passes information to a scheduler within the SOM that determines the resources available for the completion of the activity. Core MIDAS uses a procedurally-based language invoking a series of predetermined goal-oriented behaviors (tasks). The environment triggers activities (procedures) within the virtual operator and the virtual operator completes the desired procedure in accordance with their resource availability, their goals and their priorities. The scheduler invokes rules to determine the triggering of procedures. Procedures can be postponed, suspended, working, current, or pending. In turn the SOM selects activities to perform, some of which interact with the representation of equipment in the simulated world and change the behavior of the relevant part of the system. This series of actions and interactions among the structures within the HOOTL software is key when attempting to model perceptions and interpretation (characteristics of human cognition) of information from the world state. These perceptions and interpretations

impact the physical performance of a task because without perception and interpretation of the external environment, there cannot be an accurate response of the virtual operator.

4. HUMAN ERROR AND CONTEXTUAL EFFECTS

Reason (1990) defines human error as being the failure of planned actions to achieve their desired output. Reason indicates that failures can occur in one of two ways. The action may conform to the plan but the plan is inappropriate for achieving the desired goals, a failure at the planning stage; or the plan is adequate but the actions deviate from the plan, a failure of execution. Reason indicates that errors can be reduced or eliminated by improving information sources within the workplace. In Reason's classification, errors are attributed as being either active human failures or latent human failures. Active human failures are failures that are committed by those in direct contact with a system. Latent failures are loopholes in the system's defenses and are points in the system where the potential for human error has existed for some time. Explanations for the latent error classification surrounds skill-based, rule-based and knowledge-based performance. The physical world is one that is characterized by skill-based rule mechanisms guiding the completion of performance on a task whereas the cognitive world is one that is characterized by knowledge-based mechanisms. Skill-based mechanisms are those mechanisms that are associated with routine, highly practiced tasks while the knowledge-based mechanisms are those that are characteristic of novel, difficult or dangerous tasks (Reason, 1990). Reason's human error concept is organizationally defined but has its etiology in identifying the root causes of human error that are associated at an individual level.

Hollnagel (1993) further refines this definition of human error to one that is specifically aimed at predicting human error in cognition. He indicates that cognitive errors can be viewed according to how they account for the underlying causes of actions. Hollnagel indicates that erroneous behavior can be viewed as resulting from sequential/procedural errors or contextual factors. The procedural model of cognition is a normative model indicating how a task should be carried out. Any deviation to this plan results in an error. The contextual control model of cognition concentrates on how the control action selection occurs, rather than focussing on the adequacy of the sequences of actions for attaining the goal. Technological increases in the human-system integration environment are often accompanied by increases in a reliance on human cognitive abilities for successful performance and these higher cognitive processes are characterized by higher error rates (Hollnagel, 1993; Reason, 1990). Given this relationship, it is being proposed that the use of cognitive modeling tools that possess validated memory representations will be useful in pinpointing vulnerable areas that are environmentally associated (contextual manipulations).

To date, HOOTL researchers have paid little attention to the environment's impact on the behavioral predictions generated by their cognitive models and the link between the behaviors and the cognitive processes required by a given situation. One theory that attempts to provide such a link is Hollnagel's (1993) contextual control model (CoCoM) through its cognitive processing module. CoCoM states that a person's comprehension and action depends on how a context is perceived and interpreted. The purpose of the cognitive processing module within CoCoM is to meet a particular goal. This goal is satisfied by actively referring to the environment, to knowledge, or to cognitive processes as opposed to passively responding to the environment. WM plays into this process by storing contexts, which, in turn, trigger relevant answers. These WM modules are sequenced by WM storage. CoCoM views human performance as determined for the most part by the context that characterizes the environment of the human operator and the performance of the individual operator occurs as a result of the active planning ongoing by the individual operator in response to the environment. Hollnagel (1993) proposes that the actions that are carried out by the human can fail to achieve their goal as a result of accurate performance according to an inadequate plan (cognitive planning error) or deficient performance (physical error) in carrying out a successful plan. Hollnagel argues that research surrounding human error appears to confuse the causes of the events surrounding human error with the internal psychological processes or cognitive mechanisms that are presumed to explain the action (cause of event versus class of actions). CoCoM, represented in Figure 2, outlines the inter-relationship among human internal cognitive mechanisms and control levels on behavioral outcomes. All of these mechanisms demonstrate the impact that context has on impacting the performance of the

individual in the environment rather than by an inherent relation between actions.
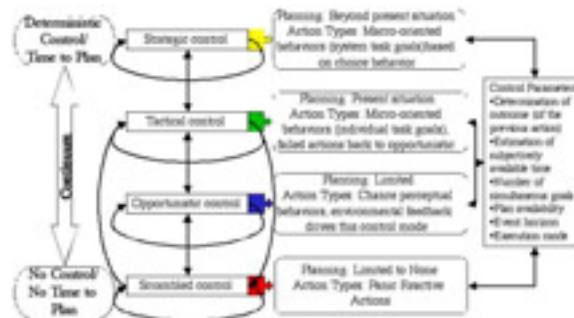

Figure 2. Representation of Hollnagel's Contextual Control Model

5. CURRENT NASA ARC HUMAN ERROR MODELING EFFORT

Current NASA research efforts have focussed on creating dynamic models of human performance and, more recently, on anticipating human errors that have significant system-level impact. One area under investigation at NASA ARC is in the area of surface operations during low-visibility operations. A suite of displays has been designed and studied at NASA ARC called the Taxiway Navigation and Situation Awareness (T-NASA) Display Suite (Foyle et al, 1996) which is comprised of a taxi head-up display (HUD), and an electronic moving map (EMM). This provides the aircrew with in-cockpit representations of external world information that is either missing or degraded in low-visibility. The introduction of these technologies may however change the nature of the operator's tasks, responsibilities, situation awareness, and the operator's error pattern from current-day surface operations (Hooey, Foyle, & Andre, 2000). Generated human performance predictions of the baseline conditions will set the stage for comparisons to human performance when technological introductions are made. In order to generate a sufficiently valid model of error predictions, it was determined that modelers using Air MIDAS will model the equipment (physical aircraft), the crew-station and external environment at varying levels of fidelity depending on the importance of the information for updating the operator's world. A representation of the information-state of the crew-station (taxi EMM and HUD) will be created in order to generate error patterns for the virtual operator based on the contextual information gained during the scenario. This representation will require attentional synchronization between the attention/perception module and the environment module of the scenario within Air MIDAS. This change is expected due to the emergent behaviors that will be elicited from the virtual operators in the environment. The control modes in Air MIDAS that have the potential to be sensitive to manipulations include UWR discrepancies, procedural memory errors, and memory load errors. These have the potential for impacting safety in the occupational environment.

The first error classification, UWR discrepancy errors, is one where there is a worldview inconsistency between two virtual operators in the environment. This contextual error occurs when one virtual operator erroneously "thinks" a different virtual operator has received information. This inconsistency results in a surprise effect on the virtual operator in the model. This error arises because of informational differences being provided to the operators. The second error type, procedural memory errors, includes errors that occur when virtual operators forget the active procedure as a result of having too many procedures of the same type operating at the same time. The occurrence of this procedural/sequential error will be modeled by scheduling the environment to cause multiple competing behaviors to occur concurrently and invoke the procedure scheduler (dropped tasks = procedural memory loss). The third type of error, memory load errors, can occur as a result of information competing for WM space. When there are a number of items needing to occupy WM, one item in WM may need to be shifted out of the limited capacity store by the subsequent information from the pilot or from the controller communication. This information is lost if it not written down to a location from an actively available list from which the operator is able to visually encode the information (for example a taxi clearance). We will cause this to occur by increasing the number of items in WM (by increasing the active procedures) and observe the effect of the task procedures on the memory load and memory onset and finish times of the procedures. Each type of error will emerge as a result of the scenario requirements and demands placed on the virtual operators. These requirements and demands will impact the creation of the cognitive plan of the virtual operator and result in performance effects. For example, the model may predict accurate performance in the face of an inaccurate plan, or the model may predict inaccurate performance in the face of an accurate plan.

6. CONCLUSION

This methodological paper has demonstrated that advances are being made in computational cognitive modeling tools and that attempts to create dynamic computational models of human error are ongoing. A critical aspect of the methodology is the interaction that exists among the physical and cognitive structures in completing a specific job. The identification of mechanisms involved in the creation of error will certainly lead to a better understanding of the concepts underlying human performance, and will lead to more solid computational predictive tools of human performance, especially in the increasingly complex and automated work environment. This computational job analysis methodology permits the Occupational Safety Practitioner the ability to generate a closer link between the job, the use of the automation and the human performer complete with their physical and cognitive abilities. This coupling is critical if the tools that are being generated today will be useful in accomplishing the ultimate goal of accurately predicting human performance in the increasingly complex and increasingly cognitive work domain.

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